

Biological and Chemical Microstructure in Coastal Areas

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LONG-TERM GOALS

We seek to gain a quantitative understanding of the physical, chemical, biological, and optical dynamics that structure the planktonic ecosystem *on the scales of the organisms*. By quantifying the variability of the organisms and their environment at the scales that the organisms live their lives, we will gain insight into the dynamics that create structure and influence the function of the planktonic ecosystem.

OBJECTIVES

Our objectives in this phase of the proposed work were to develop image-processing algorithms to allow enhanced and automated analysis of the images obtained with our free-falling planar laser imaging fluorometer (PLIF) system (FIDO- ϕ). We also interfaced the imaging system with an optical nitrate sensor and microstructure profiler.

APPROACH

FIDO- ϕ is a free-falling vehicle carrying a laser, sensitive CCD camera, computer, depth/tilt/roll sensors, and a CTD/fluorometer/transmissometer package (Fig. 1). The laser is formed into a 6.5 mm thick sheet that extends at a 45° angle below the vehicle. Chlorophyll *a* fluorescence stimulated by the laser is imaged by the camera, oriented at 90° to the laser sheet. The imaging area is 32x32 cm, with 312x312 μm resolution per pixel. Previous work has shown that the system can detect individual cells at least as small as 5 μm ; the fluorescent organisms appear as individual bright points in the images.

Recently we have modified the single-wavelength PLIF to obtain images at 2 wavelengths: 685 nm (chlorophyll *a* fluorescence), and 532 nm (scattered light from the laser). We use a filter wheel to rotate the appropriate filter in front of the camera. Successive images of fluorescence and scattering are

made close enough in time that the same particles can be identified in both images, and also in subsequent pairs of images (which allows particle tracking).

The vehicle falls at a prescribed rate (usually 3-10 cm/s), changing its buoyancy via pistons at a predetermined depth, and returning to the surface. Fluorescence images are acquired every 2 seconds, resulting in 150-800 images per profile, depending on drop speed. Data are dumped via WiFi while the vehicle is at the surface, and the vehicle can be re-programmed (shutter speed, drop speed, etc.) for subsequent drops. Depending on battery power and depth, 3-4 profiles can be made for each deployment, lasting about 2 hours.

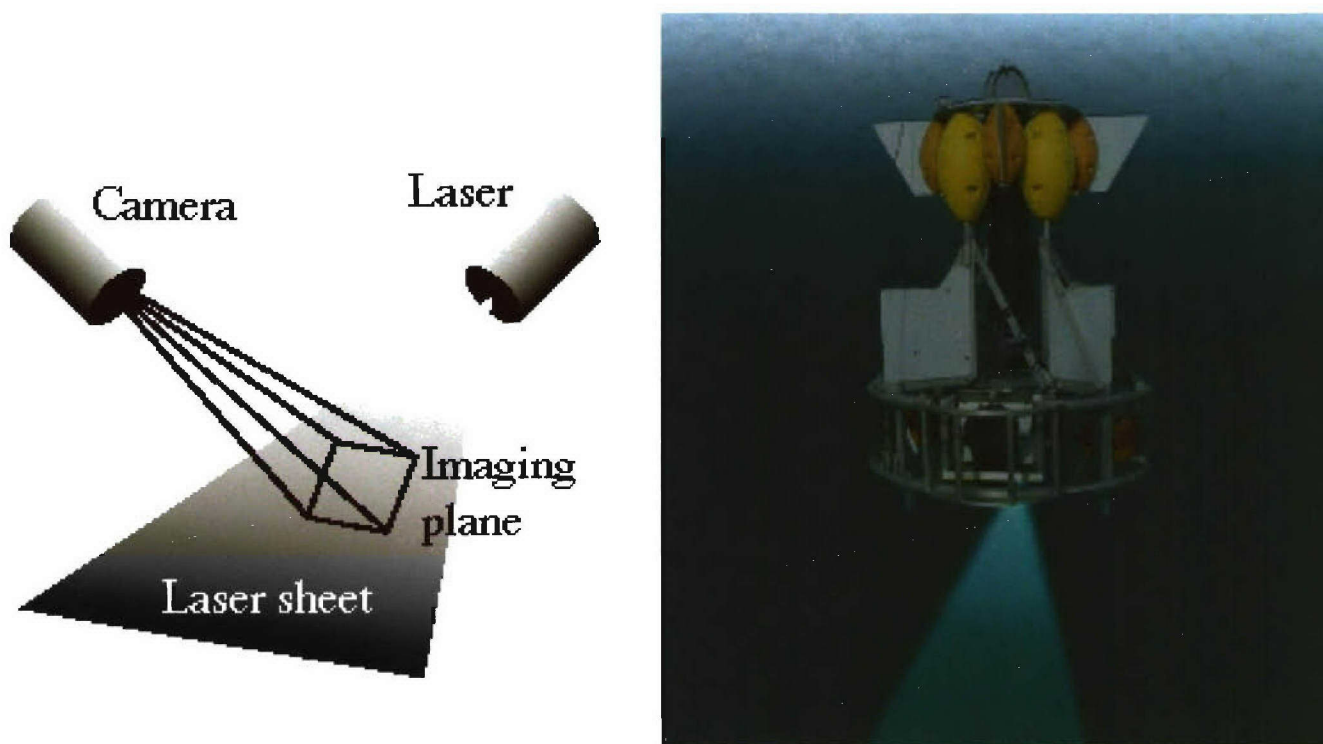


Figure 1. Left panel: Arrangement of the laser sheet, camera, and imaging plane in our PLIF system. Right panel: The FIDO- ϕ as it might appear beneath the surface, showing the laser sheet extending at 45° below the vehicle as it falls. The FIDO- ϕ is about 3 m tall, 2 m wide, and weighs about 1000 kg in air.

WORK COMPLETED

We deployed the single-wavelength FIDO- ϕ system at stations about 10 km off San Diego, CA. The bi-spectral imaging system was deployed at stations in the Santa Barbara Channel during a phytoplankton bloom that reached $>50 \mu\text{g/l}$ of chlorophyll a . Auxiliary instruments on the FIDO- ϕ frame included an SBE-19 and SBE-49 CTD, Wetstar fluorometer, ISUS optical nitrate sensor, SCAMP microstructure profiler, and an RDI downward-looking 1200 kHz ADCP. During the Santa Barbara Channel cruise, Prof. Hidekatsu Yamazaki (Tokyo University of Marine Science and technology) and his team joined us and deployed the TurboMAP turbulence profiler while the FIDO- ϕ was in the water. Additional data are obtained from the shipboard ADCP and CTD/rosette, and water samples are taken for phytoplankton cell counts and size-fractionated chlorophyll extractions.

RESULTS

The images of chlorophyll *a* fluorescence clearly show individual phytoplankton cells, aggregates, and probably herbivorous zooplankton guts with undigested food. These images provide a unique form of data: the two dimensional distribution patterns of individual phytoplankton, undisturbed, in the ocean. From the images we have begun quantifying spatial patterns of individual cells, the vertical distributions of the fluorescent particle size-abundance spectra, and the vertical variations of cell types.

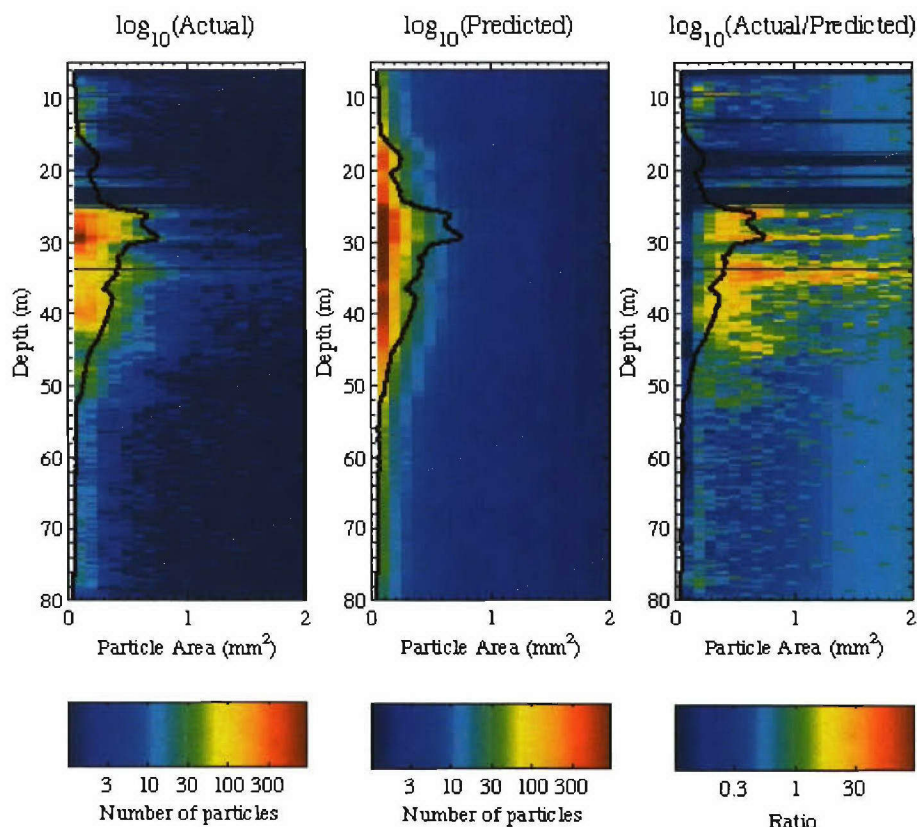


Figure 2. Particle area-abundance profile from Drop 14 of the FIDO- ϕ . Left panel: Area-abundance spectra of fluorescent particles. Black line on all plots is the total chlorophyll *a* profile. Middle panel: Area-abundance spectra predicted from the empirical relationship of the slope and intercept of the spectra to the total chlorophyll. Right panel: ratio of the observed and predicted spectra. Note the unusual layer of large particles at 35 m. Horizontal blue stripes show regions where the images were smeared due to vertical shear, and removed from analysis.

Profiles of the size-abundance spectra of fluorescent particles show a strong relation of the abundance of particles with the total chlorophyll (Fig. 2). In regions of higher total biomass, the size-abundance spectrum had a higher intercept and a steeper slope. This implies that there are more of all cell sizes in regions of high biomass; however the largest cells are only found in these regions. These large particles often formed thin (2-3 m thick) layers. We often observed marked changes in the size-abundance spectral slope with depth. These changes (and the implied changes in phytoplankton community structure) were often larger over 1 m vertically than over 1000 km horizontally at a single depth. While the bulk trends of the size-abundance spectra were well predicted by empirical relationships with the total chlorophyll, there were often unusual layers that could not have been

predicted from the fluorescence profile (e.g., Fig. 2, 35 m). These thin layers were not layers of high biomass, but were clearly composed of distinct cell types, based on the fluorescent object shapes in the images.

We frequently observed unpredictable layers of cell types (e.g., large cells, long cells, thin cells, etc.). These layers were quite apparent in the images, but were invisible to a “regular” fluorometer that just measured total chlorophyll *a* fluorescence. There were no obvious variations in total chlorophyll that would have indicated the presence of these distinct layers. The ubiquity of these *cryptic layers* shows that the phytoplankton community is highly structured, though the bulk chlorophyll may vary smoothly. One likely mechanism for the formation of these layers is the vertical shearing of existing patches of phytoplankton. The biomass (total chlorophyll) is likely controlled by large-scale external forcings (light and nutrients), while the cell types making up this biomass are a result of stochastic factors such as initial conditions, grazing, turbulence, competition, etc. As horizontally distinct communities with the same biomass are acted upon by the vertical shear, they become vertically interleaved, forming thin, layered structures in vertical profiles. The processes generating horizontal patchiness and vertical shear are occurring constantly; we predict that cryptic layers are a common and expected feature of marine planktonic ecosystems.

Our images give the two-dimensional locations of all the fluorescent particles in that volume of water. We were curious how the cells were arranged relative to one another. Based on intuition and previous work, we expected to find cells clumped at some spatial scale. To quantify the distribution patterns of individual particles we used the pair correlation statistic. This statistic quantifies departures from randomness at a range of scales. The smallest scale is about twice the resolution of the camera (~0.65 mm in this case), while the largest scale is about the size of the image (~10 cm). We were surprised to find that the pair-correlation statistic showed that throughout water column, the fluorescent particles in our images were *randomly distributed* on scales of 10 cm and less. Spatial gradients in particle numbers are apparent over larger vertical scales, so there is a transition from randomness to significant gradients at about 10 cm. This transition represents a changing balance of biological stratification vs. turbulent homogenization. With no turbulent mixing, the phytoplankton would be arranged in thin, stable layers according to the light gradient and the diffusion of nutrients. Turbulence tends to erode this stratification, leading to a random distribution of cells at the smallest scales. We are currently developing theory to quantify the dynamics linking biological stratification and turbulence to the observed distribution patterns. It is likely that the vertical patch scales will be predictable based on measurements of dissipation and density stratification. From this we should be able to predict, for example, how far a zooplankter would have to forage to find a significant change in phytoplankton concentration, given a certain stratification and dissipation.

Mounting the ISUS nitrate profiler and the SCAMP microstructure profiler on the FIDO has allowed us to make the first highly resolved estimate of vertical nitrate flux (Fig. 3). While we need to be cautious in interpreting such limited data, it is intriguing that the peak nitrate flux occurs in a thin layer at the center of the thicker subsurface chlorophyll maximum. This is consistent with phytoplankton incorporating the nitrate, and then becoming vertically mixed, forming a thicker layer than the original layer of high nitrate flux. We have a great deal more of this type of data from our recent cruise to the Santa Barbara Channel, along with better measurements of the turbulent dissipation. These data should help us formulate and test models of the dynamics supporting the deep chlorophyll maximum.

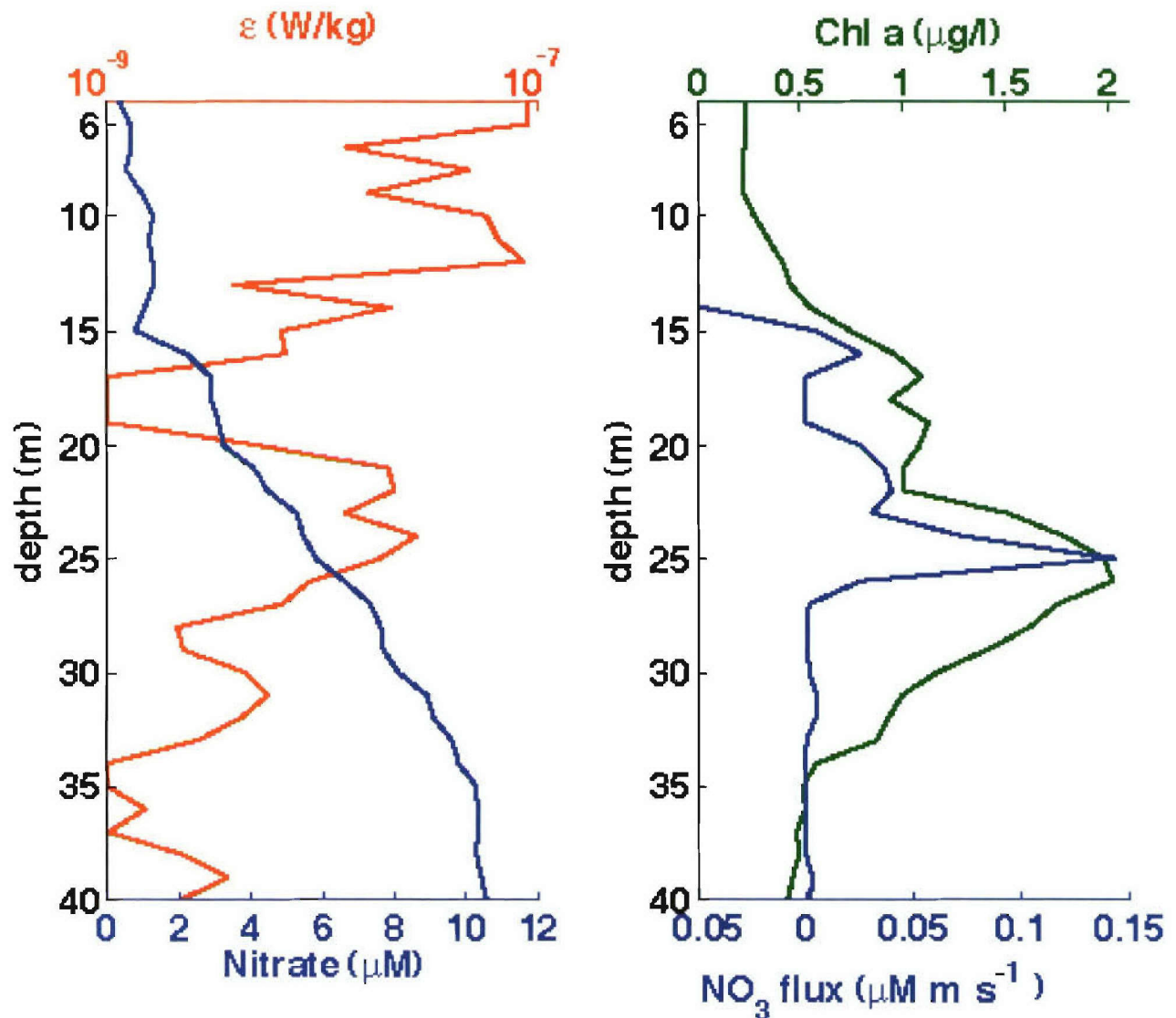


Figure 3. Left panel: Vertical profiles of the dissipation rate of turbulent kinetic energy (ε), and nitrate concentration. Right panel: Vertical profiles of chlorophyll a concentration and the vertical nitrate flux, calculated as $\kappa_v \partial \text{NO}_3 / \partial z$, where the vertical diffusivity $\kappa_v = 0.2 \varepsilon N^{-2}$. Note that the peak upward nitrate flux occurs in the subsurface chlorophyll maximum.

IMPACT/APPLICATIONS

The results of our research will have a significant impact on our understanding of the factors controlling zooplankton feeding and foraging in the ocean, and the role of physical dynamics in structuring the planktonic community on scales of centimeters to 100 meters.

RELATED PROJECTS

In our NSF-OTIC sponsored project with Stephen Monismith (Stanford University) we have built and deployed a free-falling stereo particle image velocimetry system. By taking a rapid series of images of

scattered light, followed by images of fluoresced light (both chlorophyll *a* and phycoerythrin fluorescence), we will be constructing three-dimensional velocity vectors with mm-cm spatial resolution over the imaging plane.

PUBLICATIONS

Franks, P.J.S. 2005. Plankton patchiness, turbulent transport, and spatial spectra. Mar. Ecol. Prog. Ser. 294:295-309. [published, refereed]

Franks, P.J.S. and J.S. Jaffe. Microscale variability in the distributions of large fluorescent particles observed *in situ* with a planar laser imaging fluorometer. J. Mar. Syst. [in press, refereed]

HONORS/AWARDS/PRIZES

P.J.S. Franks. 2005. SIO Best Teacher award.

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14. ABSTRACT <p>We developed and deployed a 2D planar laser imaging fluorometer system mounted on a free-falling vehicle. The vehicle also carried a CTD/fluorometer, an optical nitrate sensor, and a microstructure profiler, to acquire vertical profiles of particle fluorescence and chemical and physical distributions in the field. Our data, gathered 10 km offshore of San Diego, showed large variations in fluorescent particle properties (size-frequency distributions) with depth, with changes over 2-5 m that were larger than changes seen at a single depth over 1000's of kilometers. The phytoplankton were randomly distributed over scales <10 cm, but showed pronounced gradients over larger scales. Layers ~1 m thick of unusual particle properties (e.g., large particles, or long particles) were common, though these layers did not appear as features in the total fluorescence profiles. Such cryptic layers are likely a common occurrence, driven by the interleaving of existing horizontal patches by the vertical shear.</p>					
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